Accessing the distribution of linearly polarized gluons in unpolarized hadrons

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Abstract. Gluons inside unpolarized hadrons can be linearly polarized provided they have a nonzero transverse momentum. The simplest and theoretically safest way to probe this distribution of linearly polarized gluons is through $\cos 2\phi$ asymmetries in heavy quark pair or dijet production in electron-hadron collisions. Future Electron-Ion Collider (EIC) or Large Hadron electron Collider (LHeC) experiments are ideally suited for this purpose. Here we estimate the maximum asymmetries for EIC kinematics.

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INTRODUCTION

Linearly polarized gluons in an unpolarized hadron, carrying a light-cone momentum fraction x and transverse momentum $\boldsymbol{p}_T$ w.r.t. to the parent's momentum, are described by the transverse momentum dependent distribution (TMD) $h_1^{\perp\,g}(x, \boldsymbol{p}_T^2)$ [1, 2, 3]. Unlike the quark TMD $h_1^{\perp\,q}$ of transversely polarized quarks inside an unpolarized hadron (also frequently referred to as Boer-Mulders function) [4], $h_1^{\perp\,g}$ is chiral-even and T-even. This means it does not require initial or final state interactions (ISI/FSI) to be nonzero. Nevertheless, as any TMD, $h_1^{\perp\,g}$ can receive contributions from ISI or FSI and therefore can be process dependent, in other words, non-universal, and its extraction can be hampered in nonfactorizing cases.

Thus far no experimental studies of $h_1^{\perp\,g}$ have been performed. As recently pointed out, it is possible to obtain an extraction of $h_1^{\perp\,g}$ in a simple and theoretically safe manner, since unlike $h_1^{\perp\,q}$ it does not need to appear in pairs [3]. Here we will discuss observables that involve only a single $h_1^{\perp\,g}$ in semi-inclusive DIS to two heavy quarks or to two jets, which allow for TMD factorization and hence a safe extraction. The corresponding hadroproduction processes run into the problem of factorization breaking [3, 5].

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AZIMUTHAL ASYMMETRIES

We first consider heavy quark (HQ) production, $e(\ell)+h(P)\to e(\ell')+Q(K_1)+\overline{Q}(K_2)+X$, where the four-momenta of the particles are given within brackets, and the heavy quark-antiquark pair in the final state is almost back-to-back in the plane perpendicular to the direction of the exchanged photon and hadron. We look at the heavy quarks created in the photon-gluon fusion process, which can be distinguished kinematically from intrinsic charm production; e.g., from the $Q\overline{Q}$ invariant mass distribution. The calculation proceeds along the lines explained in Refs. [2, 6]. We obtain for the cross section integrated over the angular distribution of the back-scattered electron $e(\ell')$:

$$\frac{d\sigma}{dy_1\,dy_2\,dy\,dx_B\,d^2\boldsymbol{q}_T\,d^2\boldsymbol{K}_\perp} = \frac{\alpha^2\alpha_s}{\pi s M_\perp^2}\,\frac{(1+yx_B)}{y^5 x_B}\left(A+B\,\boldsymbol{q}_T^2\cos 2\phi\right)\delta(1-z_1-z_2)\,. \quad (1)$$

This expression involves the standard DIS variables: $Q^2=-q^2$, where q is the momentum of the virtual photon, $x_B=Q^2/2P\cdot q, y=P\cdot q/P\cdot\ell$ and $s=(\ell+P)^2=2\,\ell\cdot P=2\,P\cdot q/y=Q^2/x_B y$. Furthermore, we have for the HQ transverse momenta $K_{i\perp}^2=-\boldsymbol{K}_{i\perp}^2$ and introduced the rapidities y_i for the HQ momenta (along photon-target direction). We denote the proton mass with M and the heavy (anti)quark mass with M_Q. For the partonic subprocess we have $p+q=K_1+K_2$, implying $z_1+z_2=1$, where $z_i=P\cdot K_i/P\cdot q$. We introduced the sum and difference of the HQ transverse momenta, $K_\perp=(K_{1\perp}-K_{2\perp})/2$ and $q_T=K_{1\perp}+K_{2\perp}$, considering $|q_T|\ll|K_\perp|$. In that situation, we can use the approximate HQ transverse momenta $K_{1\perp}\approx K_\perp$ and $K_{2\perp}\approx -K_\perp$ denoting $M_{i\perp}^2\approx M_\perp^2 = M_Q^2+\boldsymbol{K}_\perp^2$. The azimuthal angles of $\boldsymbol{q}_T$ and $\boldsymbol{K}_\perp$ are denoted by ϕ_T and $\phi_\perp$ respectively, and $\phi\equiv\phi_T-\phi_\perp$. The functions A and B depend on $y, z(\equiv z_2), Q^2/M_\perp^2, M_Q^2/M_\perp^2$, and $\boldsymbol{q}_T^2$.

The angular independent part A is non negative and involves only the unpolarized TMD gluon distribution f_1^g, $A\equiv e_Q^2\,f_1^g(x,\boldsymbol{q}_T^2)\,\mathscr{A}^{eg\to eQ\overline{Q}}\geq 0$. We focus on the magnitude B of the $\cos 2\phi$ asymmetry, which is determined by $h_1^{\perp\,g}$. Namely,

$$B=\frac{1}{M^2}\,e_Q^2\,h_1^{\perp\,g}(x,\boldsymbol{q}_T^2)\,\mathscr{B}^{eg\to eQ\bar{Q}}\,, \quad (2)$$

with

$$\mathscr{B}^{eg\to eQ\bar{Q}}=\frac{1}{2}\,\frac{z(1-z)}{D^3}\left(1-\frac{M_Q^2}{M_\perp^2}\right)a(y)\left\{\left[2z(1-z)\,b(y)-1\right]\frac{Q^2}{M_\perp^2}+2\,\frac{M_Q^2}{M_\perp^2}\right\}\,, \quad (3)$$

$D\equiv D\left(z,Q^2/M_\perp^2\right)=1+z(1-z)Q^2/M_\perp^2$, $a(y)=2-y(2-y)$, $b(y)=[6-y(6-y)]/a(y)$.

Since $h_1^{\perp\,g}$ is completely unknown, we estimate the maximum asymmetry that is allowed by the bound

$$|h_1^{\perp\,g(1)}(x)|\leq f_1^g(x)\,, \quad (4)$$

where the superscript (1) denotes the $n=1$ transverse moment (defined as $f^{(n)}(x)\equiv\int d^2\boldsymbol{p}_T\,\left(\boldsymbol{p}_T^2/2M^2\right)^n\,f(x,\boldsymbol{p}_T^2)$). The function R, defined as the upper bound of the absolute

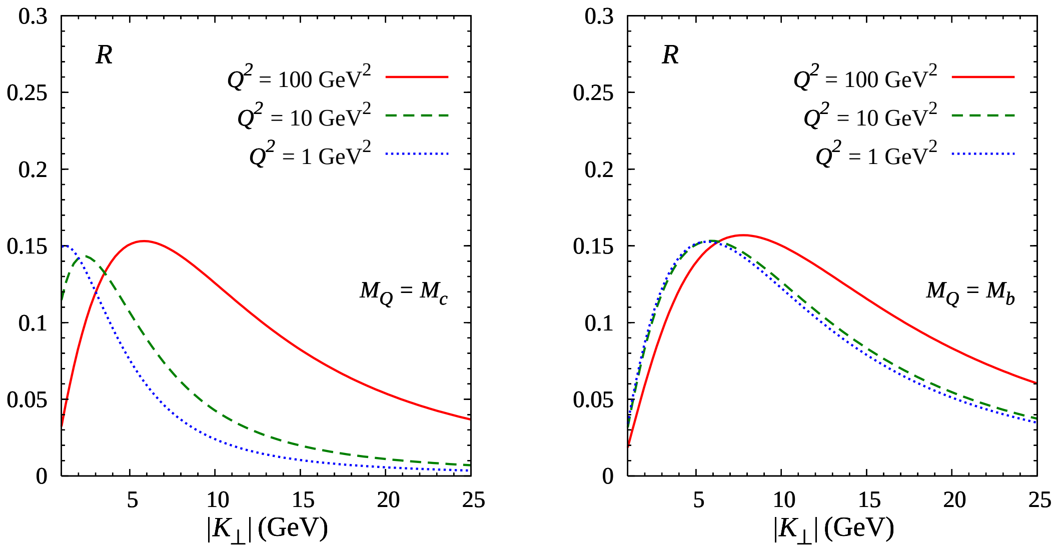

FIGURE 1. Upper bound of $|\langle\cos 2(\phi_T - \phi_\perp)\rangle|$ defined in Eq. (5) as a function of $|\boldsymbol{K}_\perp|$ at different values of Q^2, with $y = 0.01$ and $z = 0.5$.

value of $\langle\cos 2(\phi_T - \phi_\perp)\rangle$,

$$|\langle\cos 2(\phi_T - \phi_\perp)\rangle| \equiv \left| \frac{\int d^2\boldsymbol{q}_T \cos 2(\phi_T - \phi_\perp)\, d\sigma}{\int d^2\boldsymbol{q}_T\, d\sigma} \right| = \frac{\int d\boldsymbol{q}_T^2\, \boldsymbol{q}_T^2\, |B|}{2\int d\boldsymbol{q}_T^2 A} \leq \frac{|\mathscr{B}^{eg\to eQ\bar{Q}}|}{\mathscr{A}^{eg\to eQ\bar{Q}}} \equiv R\,, \tag{5}$$

is depicted in Fig. 1 as a function of $|\boldsymbol{K}_\perp|$ (> 1 GeV) at different values of Q^2 for charm (left panel) and bottom (right panel) production. We have selected $y = 0.01$, $z = 0.5$, and taken $M_c^2 = 2$ GeV^2, $M_b^2 = 25$ GeV^2. Such large asymmetries would probably allow an extraction of $h_1^{\perp g}$ at EIC (or LHeC).

If one keeps the lepton plane angle ϕ_ℓ, there are other azimuthal dependences, such as a $\cos 2(\phi_\ell - \phi_T)$. The bound on $|\langle\cos 2(\phi_\ell - \phi_T)\rangle|$, denoted as R', is shown in Fig. 2 in the same kinematic region as in Fig. 1. One can see that R' can be larger than R, but only at smaller $|\boldsymbol{K}_\perp|$. R' falls off more rapidly at larger values of $|\boldsymbol{K}_\perp|$ than R. We note that it is essential that the individual transverse momenta $K_{i\perp}$ are reconstructed with an accuracy $\delta K_\perp$ better than the magnitude of the sum of the transverse momenta $K_{1\perp} + K_{2\perp} = q_T$. This means one has to satisfy $\delta K_\perp \ll |q_T| \ll |K_\perp|$, which will require a minimum $|K_\perp|$.

The cross section for the process $eh \to e'\,\mathrm{jet}\,\mathrm{jet}\,X$ can be calculated in a similar way and is analogous to Eq. (1). In particular, the explicit expression for B can be obtained from the one for HQ production taking $M_Q = 0$, while A now depends also on x_B and receives a contribution from the subprocess $\gamma^* q \to gq$ as well, not just from $\gamma^* g \to q\bar{q}$. Therefore, the maximal asymmetries (not shown) are smaller than for HQ pair production.

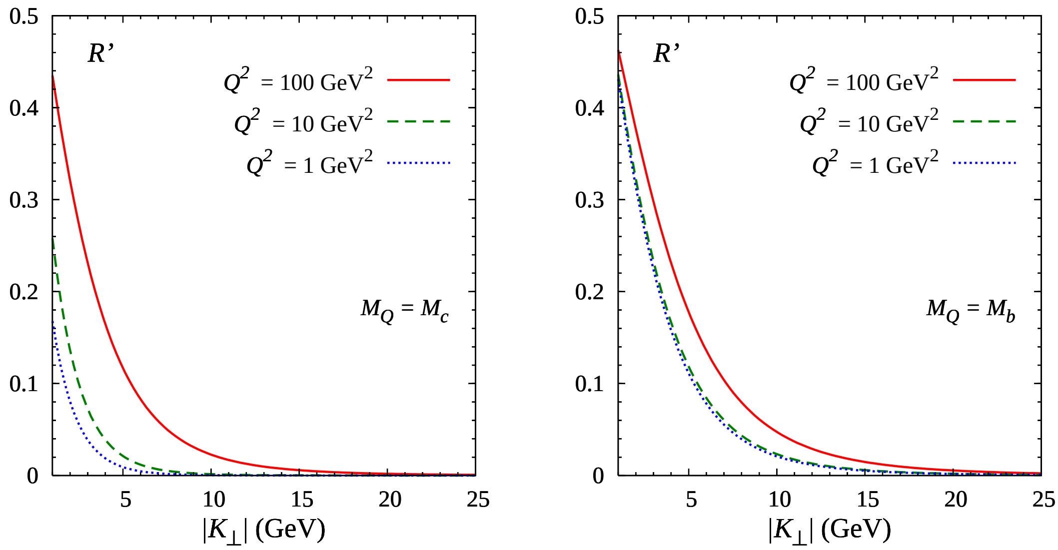

FIGURE 2. Same as in Fig. 1, but for the upper bound R' of $|\langle\cos 2(\phi_\ell - \phi_T)\rangle|$.

CONCLUSIONS

Studies of the azimuthal asymmetry of jet or heavy quark pair production in $e\,p$ collisions can directly probe $h_1^{\perp g}$, the distribution of linearly polarized gluons inside unpolarized hadrons. Breaking of TMD factorization is expected in $p\,p$ or $p\,\bar{p}$ collisions, hence a comparison between extractions from these two types of processes would clearly signal the dependence on ISI/FSI. The contribution of $h_1^{\perp g}$ to diphoton production has also been studied [7]. Since the proposed measurements are relatively simple (polarized beams are not required), we believe that the experimental determination of $h_1^{\perp g}$ and the analysis of its potential process dependence will be feasible in the future.

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